PLANT SCIENCE TODAY
Vol 12(sp1): 1-10
https://doi.org/10.14719/pst.9581

eISSN 2348-1900

REVIEW ARTICLE

Seed biopriming: A promising strategy to tackle abiotic stress in plants

Vigneshwaran K[1], Lakshmi S[2*], Vanitha C[3], Anand T[3], Babu Rajendra Prasad V[4], Kavitha S[5], Venudevan B[6], Parameswari K[7] & Nelson Navamaniraj K[8]

[1]Department of Seed Science and Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[2]Directorate of Open and Distance Learning, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[3]Directorate of Seed Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[4]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[5]Centre for Students Welfare, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[6]Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Aruppukottai 641 007, India
[7]Department of Sericulture, Forest College and Research Institute, Mettupalayam 641 001, India
[8]Controller of Examination, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Correspondence email - slakshmi@tnau.ac.in

Received: 23 May 2025; Accepted: 31 july 2025; Available online: Version 1.0: 07 October 2025

Cite this article: Vigneshwaran K, Lakshmi S, Vanitha C, Anand T, Babu RPV, Kavitha S, Venudevan B, Parameswari K, Nelson NK. Seed biopriming: A promising strategy to tackle abiotic stress in plants. Plant Science Today. 2025; 12(sp1): 1-10. https://doi.org/10.14719/pst.9581

Abstract

Abiotic stresses such as drought, salinity, high temperatures and heavy metal toxicity significantly reduce crop yield and threaten global food security. Seed biopriming is an eco-friendly and sustainable pre-sowing strategy that enhances plant resilience to these environmental challenges. It involves the use of beneficial microorganisms to colonize seeds, triggering physiological, biochemical and molecular adaptations. Biopriming enhances seed germination, seedling vigour, root architecture and improves nutrient uptake by activating stress-responsive signalling pathways, antioxidant defence mechanisms, accumulation of osmolytes and production of secondary metabolites and plant hormones such as cytokinins and indole-3-acetic acid (IAA). Additionally, it promotes systemic resistance, leading to improved growth of plants and survival under adverse conditions. Compared to other priming methods, biopriming offers long- term benefits by establishing beneficial microbial associations that support plant health throughout the growth cycle. This review highlights the microbial agents used for biopriming, mechanism of action, benefits and current research trends of seed biopriming as a sustainable approach to mitigate abiotic stress in agriculture. Understanding and optimizing this approach can significantly contribute to sustainable agricultural practices by reducing reliance on chemical inputs, thereby preventing environmental hazards, ensuring food safety and mitigating the effects of climate change.

Keywords: beneficial microbes; biopriming; climate change; stress tolerance

Introduction

Climate change significantly affects global agricultural productivity by intensifying various abiotic stresses such as drought, salinity, extreme temperatures (including heat, freezing and chilling) and heavy metal stress. Abiotic stress affects plants throughout their life cycle, particularly during growth and development (1) and ultimately leads to a reduction in crop yield worldwide (2). The specific impacts of abiotic stress vary depending on the crop, type of stress and duration of exposure. For example, in salinity conditions compared to rice, wheat exhibits greater tolerance. The grain quality and baking quality are also less affected in wheat compared to rice under similar conditions (3). Under these circumstances, one of the most significant challenges facing the global agricultural sector is achieving agrarian sustainability, which involves minimizing stress-induced crop losses while maintaining productivity for the global population (4). This could be accomplished by developing technologies and practices that increase food productivity without negatively impacting the environment (5). Conventional plant breeding techniques like direct selection are a lengthy process, improving abiotic stress resistance in crops. Alternative techniques like genetic engineering, seed priming and plant tissue culture have significant potential for mitigating abiotic stresses and enhancing the yield of crops. These methods not only increase germination and growth rates but also protect plants against abiotic and biotic stresses, which is crucial for agricultural productivity as we face climate change. Another technique, known as biopriming, involves treating seeds with beneficial microorganisms, like bacteria or fungi before planting (6). These microorganisms help to increase germination and protect the seeds from various biotic and abiotic stresses (7, 8). This review provides an in-depth discussion of seed biopriming techniques, highlighting their advantages and applications.

Effect of abiotic stresses on crop plants

Abiotic stress causes physical, morphological, biochemical and cellular changes in plants, which ultimately affects their growth and development and leads to significant yield losses (9). The impact of various abiotic stresses is explained in Table 1.

Salinity stress

Salinity refers to the concentration of dissolved salts in soil or water, which can negatively impact plant growth and soil properties by disrupting ionic equilibrium and osmotic regulation. It poses a significant risk to agriculture, affecting approximately 1.4 billion hectares about 10 % of the Earth's total land area (10). This issue not only reduces crop productivity but also deteriorates soil properties. Salinity increases due to several factors, including the melting of glaciers, which drives saltwater into inland coastal regions; climate change-induced heat stress, which lowers groundwater levels and leads to higher salt concentrations in the soil and the excessive use of chemical fertilizers, which further exacerbates the problem (11, 12).

Plant roots absorb vital nutrients in the form of soluble salts, but an overabundance of salts disrupts ion homeostasis, ultimately suppressing the growth of plants and their productivity. In saline conditions, photosynthetic activity is severely affected. Increased salinity directly reduces chlorophyll content and decreases the efficiency of photosynthetic electron transport. This reduction in photosynthetic activity is due to lowered carbon assimilation, as CO_2 diffusion into the chloroplast is hindered (13). Salt accumulation in plant tissues compromises cell membrane integrity and reduces membrane stability (14). Minimal salinity may not significantly impact plant growth, but it can severely affect reproductive stages, leading to substantial yield loss (15).

Drought stress

Water stress induced by climate change poses a significant and sustainable risk to agriculture, constraining crop growth and productivity, thereby impacting global food security. Drought stress fundamentally alters the physio-chemical and biological characteristics of the rhizosphere, which affects soil microbial activity and crop productivity (16). Stomatal closure is the plant's initial response to drought stress, which affects gaseous exchange within plant systems, leading to a reduction in CO_2 assimilation and consequently reducing photosynthetic activity (13). Additionally, drought stress leads to a decrease in chlorophyll content due to the activity of reactive oxygen species (ROS), which also compromise membrane integrity and stability and induce lipid peroxidation (13, 17). Thus, stomatal closure due to drought stress severely hampers photosynthetic efficiency, gas exchange, plant growth and overall yield.

Heat stress

Heat stress refers to the adverse physiological and biochemical effects experienced by plants due to exposure to elevated temperatures beyond their optimal range. For example, in rice, the critical temperature for flowering is approximately 37.2±2 °C; temperatures beyond this range severely impact the reproductive process. Similarly, in maize, the threshold temperature for reproductive processes is approximately 37.9±0.4 °C. Temperatures above this level severely affect pollination and fertilization, while prolonged heat stress can significantly impair growth, development and overall productivity in agricultural systems. Heat stress causes a substantial impact on plant growth and yield, causing oxidative bursts that damage internal cell organelles and lead to enzyme denaturation (18).

Heavy metal stress

Heavy metals are a class of dense metallic elements that possess high atomic weights and can be toxic or poisonous at low concentrations. Heavy metals like cadmium, lead, chromium and mercury are significant environmental pollutants that accumulate in the soil due to human activities (19, 20). Heavy metal stress alters plant photochemical pathways, reduces photosynthetic pigments, inhibits growth and nutrient assimilation and ultimately leads to plant death (19, 21). This toxicity leads to the excessive accumulation of reactive oxygen species (ROS) and methylglyoxal, resulting in lipid peroxidation, protein oxidation, enzyme inactivation and DNA damage in plants (20).

Priming technique

Many techniques have been used in the 21st century to successfully prevent the negative impacts of abiotic stress on plants from the seedling to the harvest stage. One of the most cost-effective and efficient ways to diminish the effects of abiotic stresses is seed priming, particularly during the crucial seedling phase when plants are most vulnerable. Under abiotic stress, this technique improves seedling germination as well as morpho-physiological and biochemical characteristics (23). Seed priming involves three steps. The seeds are first soaked in chosen priming agents for a predetermined time. The second phase, referred to as the activation phase, is where the synthesis of proteins, protective enzymes and the formation of mitochondria take place. The last phase is the rehydration phase (24). There are a variety of seed priming techniques, each differing based on the material used for priming. These techniques include hydropriming, halopriming, osmopriming, biopriming, nutri-priming, solid matrix priming, magneto-priming and nano-priming (25). The effectiveness of each priming technique varies depending on the plant species and environmental factors (26). Among all these priming methods, biopriming has unique advantages. It not only improves seed germination and seedling vigour, but also helps plants to enhance disease resistance and stress tolerance.

Biopriming

Bio-priming is a pre-treatment technique in which seeds are soaked with biocontrol agents or plant growth-promoting rhizobacteria (PGPR), such as beneficial bacteria and fungi, to reduce the effects of abiotic stress (Fig. 1) (27, 28). Biopriming of seeds with beneficial microorganisms increases the hydrolytic enzymes activity like amylase and phytase and improves plant growth and stress tolerance (29, 30).

Table 1. Impact of various abiotic stresses on crop plants

S.no	Abiotic stress	Effect	Reference
1.	Drought stress	Reduction in plant growth, reduction in photosynthetic activity, causes stomatal closure and reduction in yield	(22)
2.	Salinity stress	Reduction in seed germination, affects seedling establishment, affects vegetative growth and causes oxidative damage	(2)
3.	Heat stress	Affects plant morphology, physiology, stunted growth, reduced plant biomass and productivity	(2)
4.	Heavy metal stress	Alters plant photochemical pathways, reduces photosynthetic pigments, inhibits growth and nutrient assimilation and ultimately leads to plant death	(19, 21)

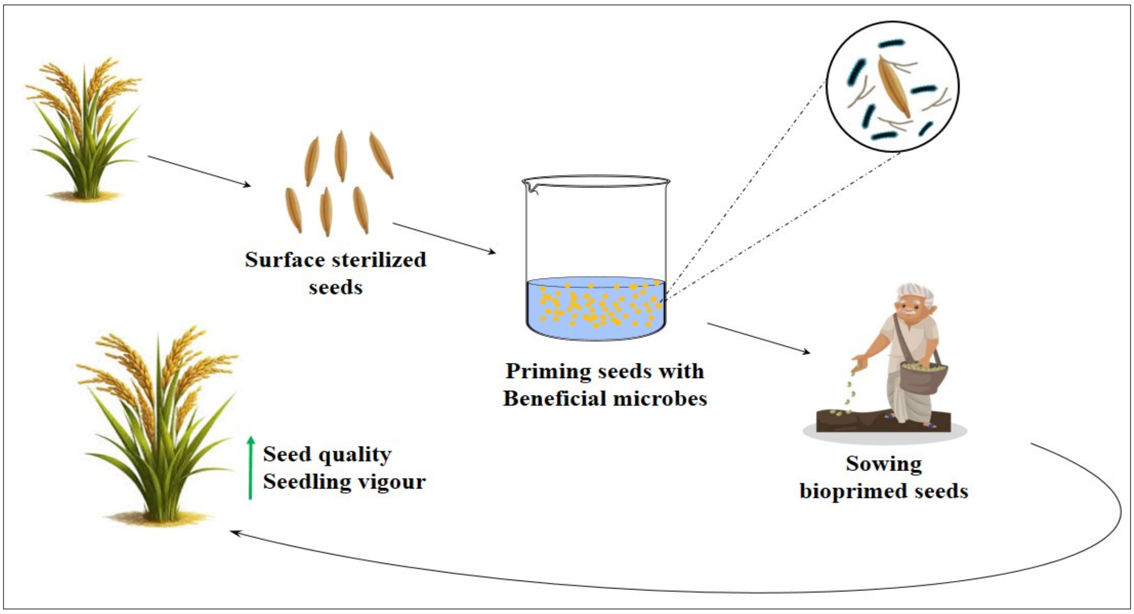

Fig. 1. Seed priming with PGPR: Process overview.

Benefits of biopriming over other priming methods

Biopriming is emerging as a valuable biological tool with many benefits in agriculture. Bio primed seeds, have high carbohydrate levels, giving plants a significant advantage in waterlogged conditions (31). While several priming techniques help to reduce abiotic stress, biopriming effectively reduces both biotic and abiotic stresses (32). Additionally, biopriming improves soil health by boosting beneficial microbial activity and enhancing nutrient uptake in plants. Its eco-friendly nature further distinguishes it from other priming methods. Compared to other priming methods, biopriming not only improves seed germination rates but also protects seeds from soil and seed-borne pathogens. Although seed hydration during priming may inadvertently promote microbial growth, the integration of antagonistic microorganisms offers an eco-friendly strategy for disease management (33, 34). Additionally, some biocontrol bacteria establish themselves in the rhizosphere directly and indirectly enhance plant health (27). Research shows that seed biopriming is more effective than conventional methods such as pelleting and film coating (35). In recent years, biopriming with plant growth-promoting rhizobacteria (PGPR) has become an integral practice in modern agriculture (36). In summary, while various priming techniques help in abiotic stress, biopriming's ability to tackle both abiotic and biotic stressors highlights its significance. Bio primed seeds offer an advantage during the early stages of germination due to their rich carbohydrate reserves, which enhance plant resilience under waterlogged conditions (31). Additionally, by serving as a sustainable alternative to chemical fungicides, seed biopriming supports environmentally friendly agricultural practices. Therefore, it deserves recognition as a potent biological tool.

PGPR-mediated biopriming- a solution to alleviate abiotic stress in plants

Biopriming with PGPR is one of the least expensive and eco-friendly approaches and it helps to improve seed germination, seedling vigour and mitigate abiotic stress (37, 38). The plant rhizosphere hosts a diverse community of microorganisms that contribute to plant growth and survival (39, 40). Several PGPR strains, including *Pseudomonas* spp. (41), *Enterobacter* spp. (42), *Bacillus* spp., *Azotobacter* spp. (43–45) and *Azospirillum* spp. (46) have been isolated and characterized as effective biopriming agents. These microorganisms enhance stress tolerance, promote nutrient uptake and improve seed germination (Table 2) (47).

Biopriming with PGPR increases the activity of hydrolytic enzymes, ROS detoxifying enzyme activity and the internal plant hormone response that protects the plant from biotic and abiotic stress (38).

Mechanisms of biopriming against abiotic stress

Antioxidant enzyme activation

Superoxide dismutase (SOD) serves as the first line of defense in plants against ROS and plays an essential role in mitigating oxidative stress caused by abiotic factors. It is an important antioxidant enzyme that converts superoxide radicals (O_2) into hydrogen peroxide (H_2O_2) and oxygen (O_2) (65). Seed priming with *T. hamatum* improved the performance of wheat seeds under salt stress, showing a 141 % increase in SOD activity (66). The activation of SOD through biopriming or other stress conditions enhances the plant's ability to cope with climatic challenges, ultimately leading to improved growth and resilience. Ascorbate peroxidase (APX) plays a crucial role in plants by detoxifying hydrogen peroxide (H_2O_2) using ascorbate as an electron donor. A study with the bacterial strain SH-8 showed a significant increase in APX levels in wheat under drought stress, which helps the plants to manage oxidative damage caused by drought (52). Catalase (CAT) plays a key role in managing H_2O_2, preventing the formation of hydroxyl radicals and protecting cellular components. It breaks hydrogen peroxide into harmless water and oxygen. Biopriming wheat seeds with *Trichoderma hamatum* showed 110 % higher CAT activity under salt stress (66). Peroxidase (POX) plays a significant role in detoxifying hydrogen peroxide and is often upregulated in response to biopriming. For instance, a study showed that priming with *Pseudomonas fluorescens* increased POX activity in rice (67). This enzymatic activity has a significant role in managing oxidative stress, particularly under abiotic stress conditions.

Phytohormonal modulation

The majority of PGPR can produce phytohormones and signalling compounds that resemble those synthesized by plants (68, 69). These hormones include indole acetic acid (IAA), gibberellic acid (GA), cytokinin and abscisic acid (ABA) (70).

Table 2. Different biopriming agents, their potential mechanism against abiotic stress

S. No	Crop	Biopriming agent	Crop response	Reference
			Drought	
1.	Soybean	*Priestua endophytica* RAE-11	•Increased shoot length, root length, RWC, total chlorophyll content, peroxidase activity and reduced H_2O_2 levels. •Phytohormone production, nutrient acquisition and antioxidant modulation.	(48)
2.	Rice	*Bacillus pumilus* sh-9	•Improved germination metrics were observed up to 15% PEG, with reductions at higher stress levels. At 35% PEG, germination was entirely inhibited. •Synthesis of phosphate solubilization and production of siderophores, sucrose, EPS and Phytohormones (IAA and ABA)	(49)
3.	Chickpea	*Bacillus licheniformis*(CPJN13S) *Pantoea agglomerans* (CPHN2)	•Improved germination percentage, leaf water status, survival percentage and accumulation of proline under drought stress conditions. •Decrease in oxidative stress markers *viz.,* MDA and H_2O_2 •Enhanced water uptake, osmoprotection and increased antioxidant activity.	(50)
4.	Soybean	*Pantoea agglomerans* (MH304295), *Bacillus subtilis* (MH304311), *Bacillus cereus* (MH333217) and *Bacillus licheniformis* (MH304284)	•Improved drought tolerance, increased root and shoot length, proline content, SOD, POD and CAT activities.	(51)
5.	Wheat	*Klebsiella aerogens* Strain SH-8	•Drought tolerance is increased by 20% •Improved Germination potential, seed vigour index, Shoot length and root length. •Production of phytohormones viz., ABA and IAA •Enhanced antioxidant enzyme activity (CAT, SOD and APX) •Production of EPS and siderophores for better nutrient uptake and protect from microbial diseases.	(52)
6.	Maize	*Enterobacter ludwigii* (OM757882)	•Enhanced drought tolerance, Germination potential is increased by 80% under drought stress induced by 20% PEG 6000, Improved seed vigour index, germination rate index, antioxidant enzyme activities such as CAT, SOD and APX, •Production ABA, IAA and Sucrose, High phosphate solubilization and siderospore production, Production of EPS aiding in biofilm formation for root attachment and stress resistance.	(53)
7.	Mung bean	Mixture of *Pseudomonas fluorescence* and *Rhizobium phaseoli*	•Improved plant height, number of leaves and root length •Increased antioxidant activities *viz.*, SOD, POD, CAT, ascorbic acid and phenolic contents. •Alleviate drought stress by enhancing antioxidant defence system, regulating ROS, Boosting nutrient uptake in roots and shoots.Reducing ethylene production via ACC- deaminase enzyme activity.	(54)
8.	Petunia	*Serratia plymuthica* MBSA-MJ1	•Increased shoot biomass by 45%, significant increase in flower numbers, shoot biomass by 26%. •Production of osmoprotectants *viz.,* proline and glycine betaine. •Enhanced plant oxidative stress defence mechanism, nutrient uptake by root colonization. •Promoting overall plant growth and stress resilience via secreted proteins and vitamins.(e.g., B- vitamins like thiamine and riboflavin)	(55)
9.	Maize	*Pseudomonas aeruginosa* *Enterobacter cloacae* *Achromobacter xylosoxidans* *Leclercia adecarboxylata*	•Improved root, shoot growth, chlorophyll a, total chlorophyll and carotenoid content under drought conditions, increases in yield per plant, photosynthetic rate and stomatal conductance. •Reduction in electrolyte leakage, Ethylene regulation through ACC-deaminase activity. •PGPR colonizes root and improves uptake of water and nutrients. •Increased IAA production and root growth. •Enhanced solubilization of phosphorous and potassium.	(56)
10.	Cumin	*Pseudomonas fluorescence,* *Trichoderma hazarium*	•Improved seed germination, seedling establishment and increased shoot length under stress •Increased APX, CAT in seeds, improved root length and increased leaf soluble proteins	(57)

Salt				
11.	Maize	*Pseudomonas geniculate* MF-84	•Increased shoot and root length, fresh and dry biomass of maize even under salt stress conditions. •Increased chlorophyll, carotenoid content, proline and soluble sugars. •Reduced uptake of harmful sodium ions •(Na+) and increased uptake of beneficial potassium ions (K+) and calcium ions (Ca+) •Stress alleviation through production of IAA to stimulate root development. •Production of EPS improves soil structure and binds Na+ reduce the availability to plants.	(58)
	Tomato	*Bacillus paralicheniformis*	•Improved speed of germination, germination percentage, seedling length, drymatter •Increased IAA production	(59)
12.	Maize	*Bacillus sp*. MGW9	•Improved germination energy, germination percentage,seedling length under salinity conditions. •Increased RWC, proline content, SOD, POD, CAT, while decreased malondialdehyde content.	(45)
Heat				
13.	Tomato, redgram, soybean and wheat	*Bacillus cereus*, *Serratia liquefaciens*, *Pseudomonas fluorescens* and *Pseudomonas putida*	•Increase in ACC-deaminase production, phytohormone level and antioxidant defense systems	(60)
14.	Soybean	*Bacillus tequilensis* SSB07	•Increase in Gibberellins, IAA and ABA contents, jasmonic acid and salicylic acid contents. •Integrated phytohormone production, enhanced anti-oxidant enzyme activity.	(61)
15.	Tomato	*Paraburkholderia phytofirmans*	•Increased chlorophyll content, Increase in sugar content, total amino acids, proline and malate. •Increased chlorophyll conductance.	(62)
Heavy metal				
16.	Chickpea	*Azospirillum brasilense*	•Increase plant growth and improved stress tolerance against chromium toxicity. •Upregulating gene expression of genes related to stress tolerance (CAT, SOD, APX, and PAL)	(63)
17.	Rapeseed	*Arthrobacter* sp., *Bacillus altitudinis* SrN9 and *Bacillus megatherium*	•Increased tolerance against cadmium by producing IAA and siderophores	(64)

(Table key: RWC- Relative Water Content, PEG- Polyethylene Glycol, IAA- Indole-3-Acetic acid, ABA- Abscisic Acid, EPS- Exopolysaccharides, MDA- Malondialdehyde, POD- Peroxidase, CAT- Catalase, SOD- Superoxide dismutase, APX- Ascorbate peroxidase, ACC- 1-aminocyclopropane-1-carboxylic acid, PAL- Phenylalanine ammonia-lyase)

Plant hormones help plants to adapt to abiotic stress by regulating their physiology and molecular responses (71). PGPR seed biopriming improves crop growth by improving phytohormone levels such as GA_3, cytokinin and auxins. While phytohormones released by PGPRs or plants after inoculation have been linked to stress tolerance, the exact mechanism remains unclear (72). These phytohormones promote root development, shoot growth and crop biomass, while also reducing abiotic and biotic stress (Fig. 2) (73).

Indole-3-acetic acid (IAA)

IAA is one of the prevalent hormones synthesised by nearly 80 % of soil microbes, including many strains of *Pseudomonas, Bacillus, Burkholderia* and *Rhizobium* species (74, 75). Numerous studies have highlighted the importance of IAA-producing PGPR in promoting plant growth and enhancing crop yield, particularly in challenging conditions like saline soils resulting from extensive agrochemical use (6, 76, 77) or drought (78, 79). Most of the PGPR can produce IAA, which stimulates root growth, root surface area and biomass. This increases the uptake of nutrients and overall growth of plants, especially under nutrient-deficient conditions (80). Higher concentrations of IAA promote lateral root development, which facilitates mineral absorption and fosters the production of root exudates, thereby enhancing bacterial colonization.

Indole-3-acetic acid (IAA) is known for its impact on the plant growth and development including cell elongation, formation of vascular tissues and apical dominance (81). Additionally, under abiotic stress, this plant hormone promotes root meristem initiation and enhances plant stress tolerance (82). A study found that wheat seeds treated with *Bacillus subtilis*, an IAA-producing bacterium, showed increased tolerance to saline conditions (83). In another research with, IAA producing- *Bacillus megaterium* and *Bacillus licheniformis* induced drought tolerance in wheat by increasing the germination index (11-46 %) promptness index (16-50 %), seedling vigour index (11-151 %), fresh weight (35-192 %), dry weight (58-226 %), relative water content, photosynthetic pigments (chlorophyll a, b and carotenoid) and osmolytes (protein and proline content) (84).

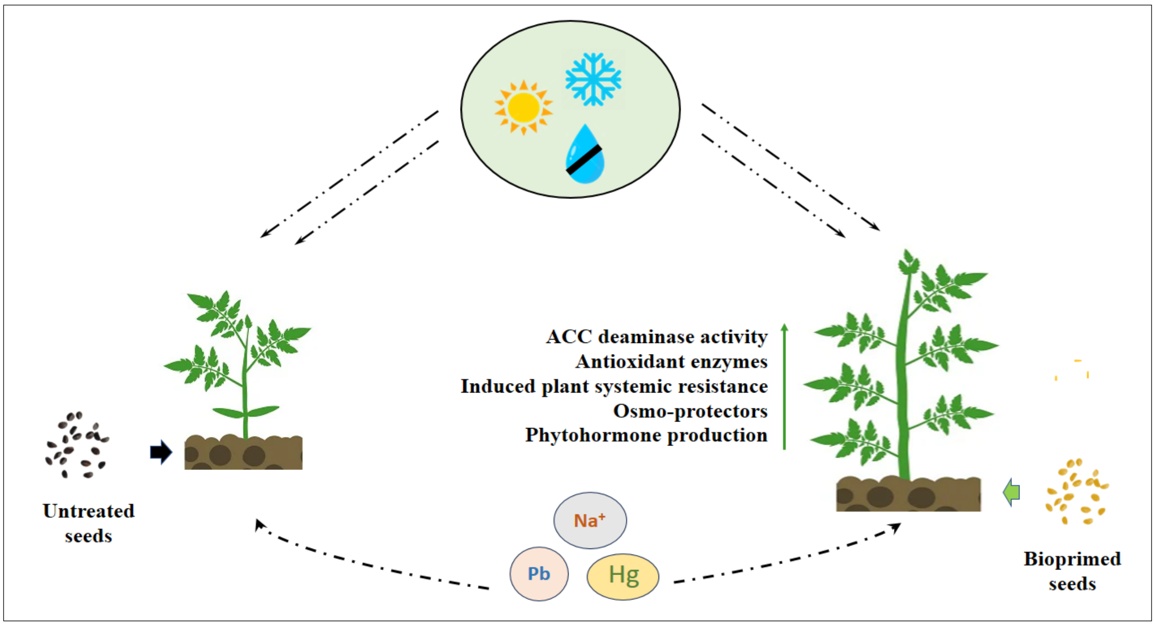

Fig. 2. Mechanisms involved in seed biopriming against abiotic stress.

Gibberellins

Gibberellins regulate plant cell division and elongation, promote hypocotyl and stem development and increase leaf and root meristem size. Gibberellins not only encourage plant development but also help to minimize the adverse effects of drought and salt stress on crops by boosting water availability. The gibberellic acid signalling system consists of DELLA proteins, which are factors that inhibit plant development during stress (82).

Cytokinins

Cytokinins regulate physiological processes including senescence, cell division, seed germination, root development, chlorophyll buildup and leaf area. Cytokinins not only regulate plant growth but also improve abiotic stress tolerance (85). In a study, soybean plants inoculated with *Azospirillum brasilense*, cytokinins delayed senescence and increased water retention under drought conditions (52).

Abscisic acid (ABA)

Some PGPR can secrete ABA, which acts in opposition to ethylene in regulating plant development and responding to abiotic stress, likely by controlling stomatal conductance (86). Research has yielded conflicting findings regarding ABA-mediated stress tolerance mechanisms, suggesting that outcomes may vary depending on both plant type and bacterial type. Certain PGPRs can produce ABA, these includes strains of *Azospirillum brasilense, Achromobacter xylosoxidans, Bacillus licheniformis, Bacillus pumilus* and various *Rhizobium* species (87) or act as stimulators of ABA under water-deficit conditions (88). Under high salinity conditions, PGPR-induced ABA signalling triggers the accumulation of ROS, which can activate calcium ion (Ca^2) channels, leading to stomatal closure and helping plants reduce water loss (89, 90). Alterations in ABA-mediated signalling pathways play an essential role in the abiotic stress tolerance mechanisms of the host plant by activating various signalling genes (91). Moreover, certain PGPR can produce polyamines that improve root structure and boost both stomatal conductance and photosynthesis. For example, Arabidopsis plants treated with a strain of *Bacillus megaterium* that produces spermidine showed lower levels of ROS and increased ABA biosynthesis.

Ethylene

Some plant growth-promoting rhizobacteria (PGPR) have a special enzyme called 1-aminocyclopropane-1-carboxylate (ACC) deaminase. This enzyme helps to break down plant ACC (92), which is crucial because it can neutralize ethylene production by converting ACC into ammonia and α-ketobutyrate. Some notable PGPR strains that carry this enzyme include certain types of *Pseudomonas oryzihabitans*, *Bacillus amyloliquefaciens* and *Burkhoderia phytofirmans*, which encourage the growth of host plant roots (80). When plants are inoculated with these ACC-deaminase-producing strains, they tend to thrive even in challenging environmental conditions, such as salt stress in rice, wheat, rapeseed, beans and tomatoes (6, 76, 77, 93, 94, 95) as well as drought stress in artichokes, maize and millet (56, 96, 97).

Nutrient mobilization

PGPRs can reduce the supplementation of nitrogen required for plant growth. They can be achieved directly by nitrogen fixation and mobilization and indirectly by supporting nitrogen-fixing bacteria through anatomical modifications of the root and root secretions. This help provided by PGPR plays a key role in enhancing nitrogen availability for plants, which in turn supports their growth and development. (68, 69, 98). Certain PGPR boost nitrogen availability indirectly by helping to increase the surface area of the root and changing the root structure (80).

Secondary metabolites

The rhizosphere is the region where soil microbes, like bacteria, fungi, viruses and archaea are in interaction with plant roots (99). Among these microorganisms, bacteria are present in greater numbers (100). Various secondary metabolites and root exudates facilitate the complex relationship between microbes and plant roots. Mediated by sugars, amino acids, organic acids and flavonoids, serving as chemical attractants in the rhizosphere region. They play a dual role, attracting beneficial soil microbes while repelling harmful phytopathogens. This delicate network of signalling regulates interactions crucial for the health and growth of plants (70).

Conclusion and Future Perspectives

Seed biopriming has emerged as a promising and eco-friendly technique to improve crop performance under abiotic stress conditions such as drought, salinity, extreme temperatures and heavy metal toxicity. By combining the benefits of traditional seed priming with the functional advantages of plant growth-promoting microbes, biopriming enhances early seedling vigour, improves germination rates and strengthens the plant's physiological, biochemical and molecular responses to stress. These include enhanced antioxidant activity, osmolyte accumulation, improved nutrient uptake and modulation of stress-responsive genes. This method is not only cost-effective and scalable but also aligns with sustainable agricultural practices by reducing dependence on synthetic agrochemicals. Despite its potential, challenges remain in improving the storability of bio primed seeds and maintaining the viability of the microbial population on them. Furthermore, integrating biopriming with advanced technologies could open new avenues for maximizing its efficacy. Thus, seed biopriming stands out as a key innovation in sustainable crop management with significant implications for improving resilience to abiotic stress. Continued interdisciplinary research and technological development will be pivotal in translating this potential into widespread agricultural applications.

Authors' contributions

VK participated in conceptualization and writing-original draft. LS, VC, AT, BV participated in conceptualization, supervision, review and editing. KS, VB, PK, NK reviewed and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Rai KK. Integrating speed breeding with artificial intelligence for developing climate-smart crops. Mol Biol Rep. 2022;49(12):11385-402. https://doi.org/10.1007/s11033-022-07769-4
2. Khan N, Ali S, Shahid MA, Mustafa A, Sayyed R, Curá JA. Insights into the interactions among roots, rhizosphere and rhizobacteria for improving plant growth and tolerance to abiotic stresses: a review. Cell J. 2021;10(6):1551. https://doi.org/10.3390/cells10061551
3. Hussain M, Ahmad S, Hussain S, Lal R, Ul-Allah S, Nawaz A. Rice in saline soils: Physiology, biochemistry, genetics and management. Adv Agron. 2017;20(1). https://doi.org/10.1016/BS.AGRON.2017.11.002
4. Edmondson JL, Davies ZG, Gaston KJ, Leake JR. Urban cultivation in allotments maintains soil qualities adversely affected by conventional agriculture. J Appl Ecol. 2014;51(4):880-89. https://doi.org/10.1111/1365-2664.12254
5. Chakraborti S, Bera K, Sadhukhan S, Dutta P. Bio-priming of seeds: Plant stress management and its underlying cellular, biochemical and molecular mechanisms. J Plant Stress Physiol. 2022;3:100052. https://doi.org/10.1016/j.stress.2021.100052
6. Sarkar A, Pramanik K, Mitra S, Soren T, Maiti TK. Enhancement of growth and salt tolerance of rice seedlings by ACC deaminase-producing *Burkholderia* sp. MTCC 12259. J Plant Physiol. 2018;231:434-42. https://doi.org/10.1016/j.jplph.2018.10.010
7. Singh U, Praharaj C, Shivay Y, Kumar L, Singh S. Ferti-fortification: an agronomic approach for micronutrient enrichment of pulses. Pulses: challenges and opportunities under changing climatic scenario. In: Proceedings of the national conference on "Pulses: challenges and opportunities under changing climatic scenario. 2015;29:208–22.
8. Zampieri E, Franchi E, Giovannini L, Brescia F, Sillo F, Fusini D, et al. Diverse plant promoting bacterial species differentially improve tomato plant fitness under water stress. Front Plant Sci. 2023;14:1297090. https://doi.org/10.3389/fpls.2023.1297090
9. Liu Y, Li P, Xu GC, Xiao L, Ren ZP, Li ZB. Growth, morphological and physiological responses to drought stress in *Bothriochloa ischaemum.* Front Plant Sci. 2017;8:230. https://doi.org/10.3389/fpls.2017.00230
10. FAO. 2024.
11. Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, et al. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change: Ipcc; 2014.
12. Buvaneshwari S, Riotte J, Sekhar M, Sharma AK, Helliwell R, Kumar MM, et al. Potash fertilizer promotes incipient salinization in groundwater irrigated semi-arid agriculture. Sci Rep. 2020;10(1):3691. https://doi.org/10.1038/s41598-020-60365-z
13. Morcillo RJ, Manzanera M. The effects of plant-associated bacterial exopolysaccharides on plant abiotic stress tolerance. Metabolites. 2021;11(6):337. https://doi.org/10.3390/metabo11060337
14. Munns R, Tester M. Mechanisms of salinity tolerance. Annu Rev Plant Biol. 2008;59(1):651-81. https://doi.org/10.1146/annurev.arplant.59.032607.092911
15. Zörb C, Geilfus CM, Dietz KJ. Salinity and crop yield. Plant Biol. 2019;21:31-38. https://doi.org/10.1111/plb.12884
16. Vurukonda SSKP, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. Microbiol Res. 2016;184:13-24. https://doi.org/10.1016/j.micres.2015.12.003
17. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SM. Plant drought stress: effects, mechanisms and management. J Sustain Agric 2009:153-88. https://doi.org/10.1007/978-90-481-2666-8_12
18. Liu M, Zhou Y, Sun J, Mao F, Yao Q, Li B, et al. From the floret to the canopy: High temperature tolerance during flowering. Plant Commun. 2023;4(6). https://doi.org/10.1016/j.xplc.2023.100629
19. Ali B, Gill RA. Heavy metal toxicity in plants: Recent insights on physiological and molecular aspects, volume II. Front Plant Sci. 2022;13:1016257. https://doi.org/10.3389/fpls.2022.1016257
20. Gill M. Heavy metal stress in plants: a review. Int J Adv Res. 2014;2(6):1043-55.
21. Feng D, Wang R, Sun X, Liu Ln, Liu P, Tang J, et al. Heavy metal stress in plants: Ways to alleviate with exogenous substances. Sci Total Environ. 2023;897:165397. https://doi.org/10.1016/j.scitotenv.2023.165397
22. Omari AF. Metabolic engineering of osmoprotectants to elucidate the mechanism (s) of salt stress tolerance in crop plants. Planta. 2021;253(1):24. https://doi.org/10.1007/s00425-020-03550-8
23. Rhaman MS, Rauf F, Tania SS, Khatun M. Seed priming methods: Application in field crops and future perspectives. Asian J Res Crop Sci. 2020;5(2):8-19. https://doi.org/10.9734/ajrcs/2020/v5i230091
24. Biswas S, Seal P, Majumder B, Biswas AK. Efficacy of seed priming strategies for enhancing salinity tolerance in plants: An overview of the progress and achievements. Plant Stress. 2023;9:100186. https://doi.org/10.1016/j.stress.2023.100186
25. Amir M, Prasad D, Khan FA, Khan A, Ahmad B. Seed priming: An overview of techniques, mechanisms and applications. Plant Sci Today. 2024;11(1):553-63. https://doi.org/10.14719/pst.2024.11.1

26. Arun MN, Hebbar SS, Senthivel T, Nair AK, Padmavathi G, Pandey P, Singh A. Seed priming: The way forward to mitigate abiotic stress in crops: Intech Open London, UK; 2022.

27. Callan NW, Mathre D, Miller JB. Bio-priming seed treatment for biological control of *Pythium ultimum* preemergence damping-off in sh2 sweet corn. Plant Dis. 1990;74(5):368–72. https://doi.org/10.1094/PD-74-0368

28. Cardarelli M, Woo SL, Rouphael Y, Colla G. Seed treatments with microorganisms can have a biostimulant effect by influencing germination and seedling growth of crops. Plants. 2022;11(3):259. https://doi.org/10.3390/plants11030259

29. Al Hijab LY, Al-Hazmi NE, Naguib DM. Rhizobacteria-priming improves common bean seeds germination under different abiotic stresses through improving hydrolysis and antioxidant enzymes kinetics parameters. Rhizosphere. 2024;29:100842. https://doi.org/10.1016/j.rhisph.2023.100842

30. Shehab GG, Ahmed OK, El-Beltagi HS. Effects of various chemical agents for alleviation of drought stress in rice plants (*Oryza sativa* L.). Not Bot Horti Agrobot Cluj-Napoca. 2010;38(1):139-48.

31. Ella ES, Dionisio-Sese ML, Ismail AM. Seed pre-treatment in rice reduces damage, enhances carbohydrate mobilization and improves emergence and seedling establishment under flooded conditions. AoB Plants. 2011;plr007. https://doi.org/10.1093/aobpla/plr007

32. Adhikary S, Naskar MK, Biswas B. Seed priming-one small step for farmer, one giant leap for food security: I application and exploration. J Pharmacogn Phytochem. 2021;10(1):409-12. https://doi.org/10.22271/phyto.2021.v10.i1h.13370

33. Fiodor A, Ajijah N, Dziewit L, Pranaw K. Biopriming of seed with plant growth-promoting bacteria for improved germination and seedling growth. Front Microbiol. 2023;14:1142966. https://doi.org/10.3389/fmicb.2023.1142966

34. Reddy PP, Reddy PP. Bio-priming of seeds. Recent Adv Crop Prot. 2013:83-90. https://doi.org/10.1007/978-81-322-0723-8_6

35. Müller H, Berg G. Impact of formulation procedures on the effect of the biocontrol agent *Serratia plymuthica* HRO-C48 on *Verticillium* wilt in oilseed rape. BioControl. 2008;53:905-16. https://doi.org/10.1007/s10526-007-9111-3

36. Timmusk S, Behers L, Muthoni J, Muraya A, Aronsson AC. Perspectives and challenges of microbial application for crop improvement. Front Plant Sci. 2017;8:49. https://doi.org/10.3389/fpls.2017.00049

37. Raj SN, Shetty N, Shetty H. Seed bio-priming with *Pseudomonas fluorescens* isolates enhances growth of pearl millet plants and induces resistance against downy mildew. Int J Pest Manag. 2004;50(1):41-48. https://doi.org/10.1080/09670870310001626365

38. Deshmukh AJ, Jaiman R, Bambharolia R, Patil VA. Seed biopriming-a review. Int J Economic Plants. 2020;7(1):38-43. https://doi.org/10.23910/2/2020.0359

39. Pérez-Jaramillo JE, Carrión VJ, de Hollander M, Raaijmakers JM. The wild side of plant microbiomes. Microbiome. 2018;6:1-6. https://doi.org/10.1186/s40168-018-0519-z

40. Genitsaris S, Stefanidou N, Leontidou K, Matsi T, Karamanoli K, Mellidou I. Bacterial communities in the rhizosphere and phyllosphere of halophytes and drought-tolerant plants in mediterranean ecosystems. Microorganisms. 2020;8(11):1708. https://doi.org/10.3390/microorganisms8111708

41. Chitra P, Jijeesh C. Biopriming of seeds with plant growth promoting bacteria *Pseudomonas fluorescens* for better germination and seedling vigour of the East Indian sandalwood. New Forests. 2021;52(5):829-41. https://doi.org/10.1007/s11056-020-09823-0

42. Roslan MAM, Zulkifli NN, Sobri ZM, Zuan ATK, Cheak SC, Abdul Rahman NA. Seed biopriming with P-and K-solubilizing *Enterobacter hormaechei* sp. improves the early vegetative growth and the P and K uptake of okra (*Abelmoschus esculentus*) seedling. PloS One. 2020;15(7):e0232860. https://doi.org/10.1371/journal.pone.0232860

43. Bidabadi SS, Mehralian M. Seed bio-priming to improve germination, seedling growth and essential oil yield of *Dracocephalum kotschyi* Boiss, an endangered medicinal plant in Iran. Gesunde Pflanzen. 2020;72(1):17-27. https://doi.org/10.1007/s10343-019-00478-2

44. Panneerselvam P, Senapati A, Kumar U, Sharma L, Lepcha P, Prabhukarthikeyan S, et al. Antagonistic and plant-growth promoting novel *Bacillus* species from long-term organic farming soils from Sikkim, India. 3 Biotech. 2019;9:1-12. https://doi.org/10.1007/s13205-019-1938-7

45. Li H, Yue H, Li L, Liu Y, Zhang H, Wang J, Jiang X. Seed biostimulant *Bacillus* sp. MGW9 improves the salt tolerance of maize during seed germination. AMB Express. 2021;11(1):74. https://doi.org/10.1186/s13568-021-01237-1

46. Gowthamy U, Selvaraju P, Hemalatha G. Standardization of seed biopriming with liquid biofertilizers on nnake gourd (*Trichosanthes cucumerina*). Int J Curr Microbiol Appl Sci. 2017;6(12):2513-24. https://doi.org/10.20546/ijcmas.2017.612.292

47. Mitra D, Mondal R, Khoshru B, Shadangi S, Mohapatra PKD, Panneerselvam P. Rhizobacteria mediated seed bio-priming triggers the resistance and plant growth for sustainable crop production. Curr Res Microb Sci. 2021;2:100071. https://doi.org/10.1016/j.crmicr.2021.100071

48. Choudhary M, Patel B, Patel M, Choudhary N, Bagatharia S, Verma RK, et al. Enhancing soybean growth under drought stress through bio-priming with desert endophyte *Priestua endophytica* strain RAE-11. Symbiosis. 2025:1-13. https://doi.org/10.1007/s13199-025-01047-0

49. Shaffique S, Imran M, Injamum-Ul-Hoque M, Zainurin N, Peter O, Alomrani SO, Lee IJ. Unraveling the new member *Bacillus pumilus* SH-9 of Bacillaceae family and its potential role in seed biopriming to mitigate drought stress in *Oryza sativa*. J Plant Stress Physiol. 2024;11:100318. https://doi.org/10.1016/j.stress.2023.100318

50. Rani S, Kumar P, Dahiya P, Gupta A, Arora K, Dang AS, Suneja P. Effect of biopriming and nanopriming on physio-biochemical characteristics of *Cicer arietinum* L. under drought stress. J Plant Stress Physiol. 2024;12:100466. https://doi.org/10.1016/j.stress.2024.100466

51. Dubey A, Malla MA, Kumar A, Khan ML, Kumari S. Seed bio-priming with ACC deaminase-producing bacterial strains alleviates impact of drought stress in soybean (*Glycine max* (L.) Merr.). Rhizosphere. 2024;30:100873. https://doi.org/10.1016/j.rhisph.2024.100873

52. Shaffique S, Imran M, Kang SM, Khan MA, Asaf S, Kim WC, et al. Seed Bio-priming of wheat with a novel bacterial strain to modulate drought stress in Daegu, South Korea. Front Plant Sci. 2023;14:1118941. https://doi.org/10.3389/fpls.2023.1118941

53. Shaffique S, Khan MA, Wani SH, Imran M, Kang SM, Pande A, et al. Biopriming of maize seeds with a novel bacterial strain SH-6 to enhance drought tolerance in South Korea. Plants. 2022;11(13):1674. https://doi.org/10.3390/plants11131674

54. Nawaz H, Hussain N, Ahmed N, Alam J. Efficiency of seed bio-priming technique for healthy mungbean productivity under terminal drought stress. J Integr Agric. 2021;20(1):87-99. https://doi.org/10.1016/S2095-3119(20)63184-7

55. Kaldate R, Singh SK, Guleria G, Soni A, Naikwad D, Kumar N, et al. Current approaches in horticultural crops to mitigate the effect of drought stress. Stress Tol Hort Crops. 2021:213-40. https://doi.org/10.1016/B978-0-12-822849-4.00004-8

56. Danish S, Zafar-ul-Hye M, Mohsin F, Hussain M. ACC-deaminase producing plant growth promoting rhizobacteria and biochar mitigate adverse effects of drought stress on maize growth. PLoS One. 2020;15(4):e0230615. https://doi.org/10.1371/journal.pone.0230615

57. Piri R, Moradi A, Balouchi H, Salehi A. Improvement of cumin (*Cuminum cyminum*) seed performance under drought stress by seed coating and biopriming. Sci Hortic. 2019;257:108667. https://doi.org/10.1016/j.scienta.2019.108667

58. Singh S, Singh UB, Trivedi M, Sahu PK, Paul S, Paul D, Saxena AK. Seed biopriming with salt-tolerant endophytic *Pseudomonas geniculata*-modulated biochemical responses provide ecological fitness in maize

(*Zea mays* L.) grown in saline sodic soil. Int J Environ Res Public Health. 2020;17(1):253. https://doi.org/10.3390/ijerph17010253

59. Parinith G, Lakshmi S, Renganayaki P, Nakkeeran S. Alleviation of salinity stress via seed priming in tomato (*Solanum lycopersicum*) with *Bacillus paralicheniformis*. Pharma Innov J. 2022;11(8):201-06.
60. Mitra D, Rodriguez AMD, Cota FIP, Khoshru B, Panneerselvam P, Moradi S, et al. Amelioration of thermal stress in crops by plant growth-promoting rhizobacteria. Physiol Mol Plant Pathol. 2021;115:101679. https://doi.org/10.1016/j.pmpp.2021.101679
61. Kang SM, Khan AL, Waqas M, Asaf S, Lee KE, Park YG, et al. Integrated phytohormone production by the plant growth-promoting rhizobacterium *Bacillus tequilensis* SSB07 induced thermotolerance in soybean. J Plant Interact. 2019;14(1):416-23. https://doi.org/10.1080/17429145.2019.1640294
62. Issa A, Esmaeel Q, Sanchez L, Courteaux B, Guise JF, Gibon Y, et al. Impacts of Paraburkholderia phytofirmans strain PsJN on tomato (*Lycopersicon esculentum* L.) under high temperature. Front Plant Sci. 2018;9:1397. https://doi.org/10.3389/fpls.2018.01397
63. El-Ballat EM, Elsilk SE, Ali HM, Ali HE, Hano C, El-Esawi MA. Metal-resistant PGPR strain *Azospirillum brasilense* EMCC1454 enhances growth and chromium stress tolerance of chickpea (*Cicer arietinum* L.) by modulating redox potential, osmolytes, antioxidants and stress-related gene expression. Plants. 2023;12(11):2110. https://doi.org/10.3390/plants12112110
64. Farhangi-Abriz S, Tavasolee A, Ghassemi-Golezani K, Torabian S, Monirifar H, Rahmani HA. Growth-promoting bacteria and natural regulators mitigate salt toxicity and improve rapeseed plant performance. Protoplasma. 2020;257(4):1035-47. https://doi.org/10.1007/s00709-020-01493-1
65. Mittler R. Abiotic stress, the field environment and stress combination. Trends Plant Sci. 2006;11(1):15-19. https://doi.org/10.1016/j.tplants.2005.11.002
66. Irshad K, Shaheed Siddiqui Z, Chen J, Rao Y, Hamna Ansari H, Wajid D, et al. Bio-priming with salt tolerant endophytes improved crop tolerance to salt stress via modulating photosystem II and antioxidant activities in a sub-optimal environment. Front Plant Sci. 2023;14:1082480. https://doi.org/10.3389/fpls.2023.1082480
67. González MC, Roitsch T, Pandey C. Antioxidant Responses and Redox Regulation Within Plant-Beneficial Microbe Interaction. Antioxidants. 2024;13(12):1553. https://doi.org/10.3390/antiox13121553
68. Jiao X, Takishita Y, Zhou G, Smith DL. Plant associated rhizobacteria for biocontrol and plant growth enhancement. Front Plant Sci. 2021;12:634796. https://doi.org/10.3389/fpls.2021.634796
69. Shah A, Nazari M, Antar M, Msimbira LA, Naamala J, Lyu D, et al. PGPR in agriculture: A sustainable approach to increasing climate change resilience. Front sustain food syst. 2021;5:667546. https://doi.org/10.3389/fsufs.2021.667546
70. Ullah A, Bano A, Khan N. Climate change and salinity effects on crops and chemical communication between plants and plant growth-promoting microorganisms under stress. Front sustain food syst. 2021;5:618092. https://doi.org/10.3389/fsufs.2021.618092
71. EL Sabagh A, Islam MS, Hossain A, Iqbal MA, Mubeen M, Waleed M, et al. Phytohormones as growth regulators during abiotic stress tolerance in plants. Front Agron. 2022;4:765068. https://doi.org/10.3389/fagro.2022.765068
72. Bukhat S, Imran A, Javaid S, Shahid M, Majeed A, Naqqash T. Communication of plants with microbial world: Exploring the regulatory networks for PGPR mediated defense signaling. Microbiol Res. 2020;238:126486. https://doi.org/10.1016/j.micres.2020.126486
73. Patten CL, Glick BR. Role of *Pseudomonas putida* indoleacetic acid in development of the host plant root system. Appl Environ Microbiol. 2002;68(8):3795-801. https://doi.org/10.1128/AEM.68.8.3795-3801.2002
74. dos Santos RM, Diaz PAE, Lobo LLB, Rigobelo EC. Use of plant growth-promoting rhizobacteria in maize and sugarcane: characteristics and applications. Front Sustain Food Syst. 2020;4:136. https://doi.org/10.3389/fsufs.2020.00136
75. Khan N, Bano A, Ali S, Babar MA. Crosstalk amongst phytohormones from planta and PGPR under biotic and abiotic stresses. J Plant Growth Regul. 2020;90:189-203. https://doi.org/10.1007/s10725-020-00571-x
76. Singh RP, Jha PN. The PGPR *Stenotrophomonas maltophilia* SBP-9 augments resistance against biotic and abiotic stress in wheat plants. Front Microbiol. 2017;8:1945. https://doi.org/10.3389/fmicb.2017.01945
77. Mellidou I, Ainalidou A, Papadopoulou A, Leontidou K, Genitsaris S, Karagiannis E, et al. Comparative transcriptomics and metabolomics reveal an intricate priming mechanism involved in PGPR-mediated salt tolerance in tomato. Front Plant Sci. 2021;12:713984. https://doi.org/10.3389/fpls.2021.713984
78. Jochum MD, McWilliams KL, Borrego EJ, Kolomiets MV, Niu G, Pierson EA, Jo YK. Bioprospecting plant growth-promoting rhizobacteria that mitigate drought stress in grasses. Front Microbiol. 2019;10:2106. https://doi.org/10.3389/fmicb.2019.02106
79. Kumar A, Patel J, Meena VS, Ramteke P. Plant growth-promoting rhizobacteria: strategies to improve abiotic stresses under sustainable agriculture. J Plant Nutr. 2019;42(11-12):1402-15. https://doi.org/10.1080/01904167.2019.1616757
80. Oleńska E, Małek W, Wójcik M, Swiecicka I, Thijs S, Vangronsveld J. Beneficial features of plant growth-promoting rhizobacteria for improving plant growth and health in challenging conditions: A methodical review. Sci Total Environ. 2020;743:140682. https://doi.org/10.1016/j.scitotenv.2020.140682
81. Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, et al. Crop production under drought and heat stress: plant responses and management options. Front Plant Sci. 2017;8:1147. https://doi.org/10.3389/fpls.2017.01147
82. Etesami H, Jeong BR, Glick BR. Potential use of *Bacillus* spp. as an effective biostimulant against abiotic stresses in crops-A review. Curr Res Biotechnol. 2023;5:100128. https://doi.org/10.1016/j.crbiot.2023.100128
83. Ji C, Wang X, Tian H, Hao L, Wang C, Zhou Y, et al. Effects of *Bacillus methylotrophicus* M4‐1 on physiological and biochemical traits of wheat under salinity stress. J Appl Microbiol. 2020;129(3):695-711. https://doi.org/10.1111/jam.14644
84. Rashid U, Yasmin H, Hassan MN, Naz R, Nosheen A, Sajjad M, et al. Drought-tolerant *Bacillus megaterium* isolated from semi-arid conditions induces systemic tolerance of wheat under drought conditions. Plant Cell Rep. 2022:1-21. https://doi.org/10.1007/s00299-020-02640-x
85. Etesami H, Glick BR. Halotolerant plant growth–promoting bacteria: Prospects for alleviating salinity stress in plants. Environ Exp Bot. 2020;178:104124. https://doi.org/10.1016/j.envexpbot.2020.104124
86. Müller M. Foes or friends: ABA and ethylene interaction under abiotic stress. Plants. 2021;10(3):448. https://doi.org/10.3390/plants10030448
87. Egamberdieva D, Wirth SJ, Alqarawi AA, Abd_Allah EF, Hashem A. Phytohormones and beneficial microbes: essential components for plants to balance stress and fitness. Front Microbiol. 2017;8:2104. https://doi.org/10.3389/fmicb.2017.02104
88. Cohen AC, Bottini R, Pontin M, Berli FJ, Moreno D, Boccanlandro H, et al. *Azospirillum brasilense* ameliorates the response of *Arabidopsis thaliana* to drought mainly via enhancement of ABA levels. Physiol Plant. 2015;153(1):79-90. https://doi.org/10.1111/ppl.12221
89. Goswami M, Suresh D. Plant growth-promoting rhizobacteria-alleviators of abiotic stresses in soil: a review. Pedosphere. 2020;30(1):40-61. https://doi.org/10.1016/S1002-0160(19)60839-8
90. Grover M, Bodhankar S, Sharma A, Sharma P, Singh J, Nain L. PGPR mediated alterations in root traits: way toward sustainable crop production. Front Sustain Food Syst. 2021;4:618230. https://doi.org/10.3389/fsufs.2020.618230

91. Zhou C, Ma Z, Zhu L, Xiao X, Xie Y, Zhu J, Wang J. Rhizobacterial strain *Bacillus megaterium* BOFC15 induces cellular polyamine changes that improve plant growth and drought resistance. Int J Mol Sci. 2016;17 (6):976. https://doi.org/10.3390/ijms17060976

92. del Carmen Orozco-Mosqueda M, Glick BR, Santoyo G. ACC deaminase in plant growth-promoting bacteria (PGPB): An efficient mechanism to counter salt stress in crops. Microbiol Res. 2020;235:126439. https://doi.org/10.1016/j.micres.2020.126439

93. Nautiyal CS, Srivastava S, Chauhan PS, Seem K, Mishra A, Sopory SK. Plant growth-promoting bacteria *Bacillus amyloliquefaciens* NBRISN13 modulates gene expression profile of leaf and rhizosphere community in rice during salt stress. Plant Physiol Biochem. 2013;66:1-9. https://doi.org/10.1016/j.plaphy.2013.01.020

94. Li H, Lei P, Pang X, Li S, Xu H, Xu Z, Feng X. Enhanced tolerance to salt stress in canola (*Brassica napus* L.) seedlings inoculated with the halotolerant *Enterobacter cloacae* HSNJ4. Appl Soil Ecol. 2017;119:26-34. https://doi.org/10.1016/j.apsoil.2017.05.033

95. Gupta S, Pandey S. ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (*Phaseolus vulgaris*) plants. Front Microbiol. 2019;10:1506. https://doi.org/10.3389/fmicb.2019.01506

96. Namwongsa J, Jogloy S, Vorasoot N, Boonlue S, Riddech N, Mongkolthanaruk W. Endophytic bacteria improve root traits, biomass and yield of *Helianthus tuberosus* L. under Normal and Deficit Water Conditi. J Microbiol Biotechnol. 2019:1777–89. https://doi.org/10.4014/jmb.1903.03062

97. Chandra D, Srivastava R, Glick BR, Sharma AK. Rhizobacteria producing ACC deaminase mitigate water-stress response in finger millet (*Eleusine coracana* (L.) Gaertn.). 3 Biotech. 2020;10:1-15. https://doi.org/10.1007/s13205-019-2046-4

98. Vacheron J, Desbrosses G, Bouffaud ML, Touraine B, Moënne-Loccoz Y, Muller D, et al. Plant growth-promoting rhizobacteria and root system functioning. Front Plant Sci. 2013;4:356. https://doi.org/10.3389/fpls.2013.00356

99. Paez-Espino D, Eloe-Fadrosh EA, Pavlopoulos GA, Thomas AD, Huntemann M, Mikhailova N, et al. Uncovering Earth's virome. Nature. 2016;536(7617):425-30. https://doi.org/10.1038/nature19094

100. Mohanty P, Singh PK, Chakraborty D, Mishra S, Pattnaik R. Insight into the role of PGPR in sustainable agriculture and environment. Front sustain food syst. 2021;5:667150. https://doi.org/10.3389/fsufs.2021.667150

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (https://creativecommons.org/licenses/by/4.0/)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.